Long-term variability of storm surge frequency in the Venice Lagoon: an update thanks to eighteenth century sea level observations

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Abstract

Sea level observations made in the Venice Lagoon between 1751 and 1792 have been re-covered, consisting of two time series of daily data on high and low waters at Venice and Chioggia. From comparisons with modern observations the quality of the 18th century data appears to be good enough to allow a useful analysis. A composite time series of daily mean sea level is obtained by merging the 18th century data and 1872–2004 observations at Venice Punta della Salute. The absence of reliable information on vertical references pre-vents the connection of the two 18th century time series with each other and with modern observations. However, daily sea level anomalies relative to the mean sea level enable to recognize storm surge events, that appear to occur more frequently in the second half of the 18th century than in the late 19th and 20th centuries, particularly during the 1751–1769 period. The record-breaking storm surge of 4 November 1966 turns out to be a remark-able event also in comparison with the events extracted from the 18th century time series. Further work is required to fill the gap between the old and modern observations.

1 Introduction

The coastal communities in the north Adriatic region and, particularly, in the Venice Lagoon have always been sensitive to sea level variations, particularly the occurrence of storm surges and related floods, locally known as *acqua alta* (high water). Therefore, it is not a surprise that ancient chronicles on that subject date back to over 1000 years ago (Enzi and Camuffo, 1995).

Storm surges in the north Adriatic are the result of synoptic atmospheric forcing variability, and they are generally induced by southerly wind (Sirocco) associated ~~to~~ with cyclones over the western or central Mediterranean. The sea level rise connected with storm surges affects the whole Venice Lagoon almost uniformly~~, however,~~. However, the interaction of the Sirocco flow with the orography surrounding the northern Adriatic can ~~determine~~ result

in a north-easterly wind flow (Bora) that produces an additional sea level increase in the Lagoon and, particularly, at its south-western end (Camuffo, 1981).

Regular and still ongoing sea level monitoring in the north Adriatic started in the second half of the 19th century (for instance, tide gauges were installed in Trieste in 1859 and in Venice in 1871), and the time series provide long-term and accurate information about Mean Sea Level (MSL) variability and storm surge frequency and intensity that has been exploited by several authors (see, e.g. Raicich, 2003, 2007, 2010; Pirazzoli et al., 2008; Lionello et al., 2012; Tsimplis, 2012; and references therein). However, earlier observations exist. The earliest quantitative observations of sea level height seem to have been made at Venice by Francesco Rinuccini in 1638 on Galileo Galilei's request by means of a pole (Rinuccini, 1966).

Sea level observations, relative to local references, were made between 1751 and 1792 at Venice, in the middle of the Lagoon, and Chioggia, at about 20 km from Venice at the south-western end of the Lagoon (Fig. 1). These data sources are particularly interesting because they provide regular observations on a daily basis made by educated persons having a scientific background (medicine, natural sciences, physics, engineering), therefore, . Therefore, although the observation methods and techniques do not comply with modern standards, they are potentially useful for an analysis in conjunction with modern data. The availability of daily observations enables to study the sea level variability on the synoptic time scale, in particular to investigate the occurrence of extreme events.

In principle, two viewpoints can be adopted to define the extreme events. One involves sea level anomalies relative to a suitable MSL (in time), which represent the effect of the atmospheric forcing, while the other makes use of sea level heights relative to a known vertical reference, accounting for the impact of the events on the coast. Unfortunately, the insufficient information about local references, in particular their stability, not only prevents adopting the second viewpoint, but it does not allow to connect the 18th century and the modern observations to a common vertical reference.

The main aim of this paper is to describe the analysis of a time series of daily sea level data useful to study the storm surge frequency in the Venice Lagoon since 1751. In the next

section the data used in this work and their sources will be described, together with the analytical methods. The methods used to derive the composite time series will be outlined in Sect. 3. Section 4 will include the analysis and discussion ~~on~~ of storm surge frequency and ~~on interannual variability from monthly means . Conclusive~~ interannual variability of monthly means of sea level. Concluding remarks will be presented in Sect. 5.

2 The data

2.1 Eighteenth century sea level

Two time series of 18th century sea level observations were recovered, namely at Venice, from 1751 to 1769, and at Chioggia, from 1779 to 1782.

The Venice time series starts in 1751 thanks to the civil architect and hydraulic engineer Tommaso Temanza (1705–1789), who recorded meteorological and sea level data on a daily basis ~~.~~ (Fig. 2, left). The observations cover the periods 1 January 1751–7 June 1757, 1 January 1765–30 June 1766 and 1 January–31 December 1769, with some minor gaps, and they are available as manuscripts (Temanza, 1751–1769). The sea level observations consist of sea flux, sea reflux and the so-called *water mass* (*massa dell'acqua* in the original), corresponding to the difference between flux and reflux, and are expressed in Venice feet and inches ($1\,\mathrm{ft} = 34.7735\,\mathrm{cm}$, $12\,\mathrm{in} = 1\,\mathrm{ft}$; Martini, 1883). ~~Flux and reflux~~ Although the Venice Lagoon is affected by a semidiurnal tide, Temanza does not report high and low waters but just one flux and one reflux per day, that very likely correspond to the daily highest and lowest sea levels, respectively~~; this~~. This information is not explicitly stated by Temanza, but, on average, their difference is consistent with the total daily sea level range observed in modern data (this point will be discussed in Sect. 3). The text accompanying the observations explicitly reads "the water height is referred to the water *comune*, which is the fixed mark identified by the greenish mucilage left by salty water on stones". The water *comune* is also known as the *comune marino* (CM). The mucilage belt consists of algae and approximately corresponds to the Mean High Water; thus, the

flux value is both above and below zero and the reflux value is almost always below zero. An open question is whether Temanza really refers his measurements to the algae belt or rather to a physical mark. In fact, a *C* used to be engraved, sometimes above a ~~horizontal segment~~short horizontal mark, at the upper edge of the algae belt on a wall or quay to indicate the CM, which would be adopted as a reference for levelling. Temanza claims the mark to be stable (relative to the ground), which is true only if it is engraved, otherwise, its position follows MSL variability, adapting to new MSL conditions in approximately 2–3 months, depending on the wave motion (A. Sfriso, Ca' Foscari University, Venice, personal communication, 2014).

From 1779 to 1792 the physician Giuseppe Vianelli (1720–1803) made observations at Chioggia ~~.~~ (Fig. 2, right). Two time series are available, partly overlapping. The main time series consists of ~~daily~~ heights and times of high and low waters from 1 January 1782 to 31 December 1792, published in the Ephemerides of Mannheim's Societas Meteorologica Palatina (Vianelli, 1784, 1785, 1786, 1787, 1788, 1789, 1790, 1793a, b, 1794, 1795). Two high and two low waters are generally observed every day because of the semidiurnal character of local tide. Another time series consists of 5-day Mean High Waters at syzygies and quadratures from 2 February 1779 to 29 December 1784, published in Chiminello (1789). During the 1782–1784 period, common to both time series, the 5-day means are verified to correspond to the averages of daily high waters; unfortunately, the daily values have not been found, therefore the information about storm surges cannot be extended back to 1779. Sea level heights are measured by means of a vertical pole divided in Venice feet and inches and are referred to the sea floor (Vianelli, 1784). ~~Times are~~ Apparent times are provided, expressed as *hora italica* (Italian time), according to which the day starts half an hour after local sunset (Vianelli, 1785). The time series is characterized by several individual missing days and short gaps, up to 10 days. Longer gaps, between 12 and 42 days, exist for unknown reasons, except those due to the observer absence in December 1787 (Vianelli, 1789), the Lagoon freezing in January 1789 (Vianelli, 1793a), and a femur fracture suffered by Vianelli that caused several interruptions from February to August 1790 (Vianelli, 1793b).

2.2 Other data

Modern sea level data used in this work come from the 1872–2004 time series of high and low waters for Venice Punta della Salute (Venice PS) (Battistin and Canestrelli, 2006), and the hourly time series for Venice PS (1940–2012) and Chioggia Vigo (1989–2012) (obtained from the Venice office of the Italian Superior Institute for Environmental Research and Protection (ISPRA), www.venezia.isprambiente.it). Cubic spline interpolation is used to estimate high and low waters at Chioggia Vigo.

Correlations with the atmospheric pressure involve the 1725–1997 time series of daily values observed at Padua, located at 35–40 km from both Venice and Chioggia (Fig. 1) (Camuffo et al., 2002).

3 Daily sea level

To avoid confusion, in this paper Venice and Chioggia represent the 18th century sea level time series and Venice PS and Chioggia Vigo identify the modern time series.

The accuracy of individual sea level measurements and times of observation is difficult to assess. From the original sources we can only deduce nominal precisions according to the least significant digits adopted, namely 1 in (about 2.9 cm) at Venice and 0.5 in (about 1.5 cm) at Chioggia. Time precision at Chioggia is 0.25 h, while the times of the sea level extremes ~~times~~ at Venice are not reported. We do not have details about the observation sites and conditions, if and how the effect of wind waves on each measurement is taken into account and if the observation is instantaneous or a sort of time average; a realistic error bar associated to an individual measurement in the most favourable conditions does not seem to be better than ± 3 cm (about ± 1 in). Times at Chioggia are converted to UTC+1 time before the data processing, ~~also~~ taking into account the annual cycle of sunset time, which marks the day start. The $-11'$ time lag, ~~for both stations,~~ corresponding to the difference between local and $15°$ E ~~longitudes~~ longitude, is also included.

The search for possible erroneous data and outliers is essentially based on the visual inspection of the time series, and, at Chioggia, on ~~a~~ the comparison between high and low waters and astronomical tidal predictions. As a result, no data of Venice and 15 data of Chioggia were considered suspect and rejected. The tidal analysis is made on the 1989–2012 data of Chioggia Vigo by means of the TASK-2000 software (Bell et al., 1999). Comparisons between observations and predictions are displayed in Fig. ~~2~~3; note the occurrence of a remarkable storm surge which lasted a couple of days with peak on 24 December 1792 (Fig. ~~2b~~3b). Clearly, tidal predictions derived from modern data represent the 18th century conditions only approximately, owing to the bathymetric and morphological changes that have occurred since then in the Venice Lagoon because of construction and excavation works (Rusconi, 1983; Camuffo and Sturaro, 2003).

A daily sea level mean is obtained by averaging the original observations for each calendar day. To compute a daily mean, at Venice both sea level extremes are required while at Chioggia there must be an equal number of low and high waters (~~normally~~ one or two). The daily sea level cycle is only approximately accounted for by high and low waters and not at all by the sea level extremes alone, therefore our daily means may significantly differ from the 24-hourly mean, which is often taken as a reliable standard. The bias can be estimated using modern Venice PS and Chioggia Vigo data. For each year and calendar day, the difference is computed between the daily mean obtained from data selected according to the same sampling schemes used in the 18th century and the daily mean obtained from 24 hourly data. These differences are averaged over the available years (1940–2012 at Venice PS and 1989–2012 at Chioggia Vigo), obtaining mean daily biases and related ~~STDs (errors)~~standard deviations, that represent errors; a 30-day running mean is then applied to reduce the effect of the outliers. As a result, on average, at Venice the daily mean sea level computed from the extremes is always lower than the 24-hourly mean, with differences varying between -4 cm in January and June and -1 cm in October, and errors around 1 cm in all months. At Chioggia the average differences between daily means computed from high and low waters and 24 hourly values vary between -0.2 cm in March to $+0.4$ cm in January, with errors between 0.2 cm in June and 0.6 cm in March~~, i. e.~~. These

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errors are of the same size as the biases and appear to be quite tolerable for a study of storm surges.

A daily sea level anomaly is obtained as the difference between the observed daily mean and a MSL computed over a suitable time interval. This is represented by the low-frequency sea level component of time scale longer than six months, as in Lionello et al. (2012), and it is estimated by means of the Objective Analysis technique (Gandin, 1965; Bretherton, 1976). Thus, the sea level anomalies are little affected by the seasonal variability of sea level due to the steric effect, the ocean circulation and the semi-annual and annual tidal constituents. Moreover, the influence of the above-mentioned biases related to the daily sea level mean computation is also removed. For this reason, the daily biases are only taken into account during the computation of the monthly means (see Sect. 4.2).

The daily anomalies obtained from 1989–2004 high and low waters at Chioggia Vigo and Venice PS are highly correlated, with $r = 0.97$ ($p \ll 0.01$); on average, Chioggia Vigo anomalies are approximately 1 % larger than Venice PS anomalies. Using Venice PS 1872–2004 time series, the daily anomalies computed from sea level extremes are, on average, less than 1 % smaller than those obtained from high and low waters. Thus, a composite time series of daily sea level anomalies can be produced by merging the 18th century sea level anomalies for Venice, with essentially no correction, those for Chioggia, reduced by 1 %, and the Venice PS anomalies obtained from high and low waters. We only take into account the data of the October–March period, when more than 90 % of the notable storm surges are observed (Battistin and Canestrelli, 2006).

To check the consistency of the 18th century sea level anomalies, we also take advantage of the inverse barometer effect. Linear regression is used to quantify the inverse relationship between sea level and atmospheric pressure anomalies, obtained from the Padua 1725–1997 time series with the same filtering procedure used for sea level. The assumption is that a poor quality of either the sea level or the pressure data causes the anomalies to be uncorrelated and/or the inverse barometer coefficient unreasonable. In general, the inverse barometer coefficient obtained by linear regression of observations does not correspond to the theoretical value at equilibrium of approximately $-1\,\mathrm{cm\,hPa^{-1}}$, obtained from depth-

integrated equations of motion (e.g. Bowden, 1983), because the observed sea level variations, that are also connected to the local and remote wind field and modulated by local bathymetry, can often depart from ideal conditions. The inverse barometer coefficient also depends on the time scales of the low-frequency component used to obtain the anomalies.

The regression of Venice and Chioggia sea level and Padua pressure anomalies gives inverse barometer coefficients of -1.1 and -0.9 cm hPa^{-1}, respectively; the linear correlation coefficients are $r = -0.6$ for both the time series. For comparison, the regressions of Venice PS and Chioggia Vigo sea levels and Padua pressure, until 1997, are characterized by coefficients of -1.3 and -1.2 cm hPa^{-1}, respectively~~. The~~, and the linear correlation coefficients are ~~$r = -0.6$ for both 18th century time series and~~ $r = -0.7$ for both ~~modern time series, all of which~~ the time series. All linear correlations are significant at $p \ll 0.01$. The inverse barometer coefficients from old and modern data differ significantly (at $p < 0.05$). This might be due to the different quality of the data and/or to the different response of sea level to atmospheric pressure variations, induced by the bathymetric changes occurred in the Lagoon in the meantime.

The analyses are limited to the October–March period, when the water column is less stratified than in spring-summer and the inverse barometer is generally more effective, but the results are identical if the whole year is taken into account.

It is possible to compare old and modern daily sea level ranges. At Venice the mean range between daily extremes increases from (69 ± 8) cm in 1751–1769 to (77 ± 5) cm in 1872–1940 and to (81 ± 5) cm in 1941–2004. Part of this change can probably be attributed to the works made since the late 19th century, that modified the propagation of the tidal signal in the Lagoon (Rusconi, 1983; Camuffo and Sturaro, 2003). The Mean Tidal Range in Chioggia, corresponding to the difference between Mean High Water and Mean Low Water, has remained essentially unchanged, from (54 ± 8) cm in 1782–1792 to (58 ± 3) cm in 1989–2012.

4 Results and discussion

4.1 Storm surges

The storm surges of interest are represented by the daily sea level anomalies that exceed three selected height thresholds, corresponding to the highest 0.1, 1 and 5 % of the 1872–2004 Venice PS anomalies obtained from high and low waters, namely 55, 37 and 25 cm, which select strong, moderate and weak surges, respectively.

For each calendar year we compute the number of events above each threshold observed from October of the previous year to March. Only complete October-March periods are taken into account, therefore remarkable events, as the storm surge observed on 24 December 1792, may not be included in the statistics. From these data average values are also obtained on pseudo-decadal basis, namely from about 9 years of data in 1751–1769 and 1782–1792, and a ~~10year~~ 10-year running mean from 1873–1882 to 1995–2004 (Fig. ~~3~~4). A sea level peak is sometimes followed by marked secondary peaks due to the fundamental seiche of the Adriatic Sea excited by the storm surge (Raicich, 1999)~~,~~. ~~therefore, .~~ Therefore, to avoid the inclusion of such events, that are not directly related to the meteorological forcing, only independent surges are considered, namely sea level anomaly peaks at least three days apart from each other.

Means and ~~STDs~~ standard deviations computed from the 1872–2004 decadal frequencies, are $(0.2 \pm 0.1)\,\mathrm{yr}^{-1}$ for strong events (Fig. ~~3a~~4a), $(1.4 \pm 0.5)\,\mathrm{yr}^{-1}$ for moderate events (Fig. ~~3b~~4b), and $(5.4 \pm 0.5)\,\mathrm{yr}^{-1}$ for weak events (Fig. ~~3c~~4c). The 1751–1769 period is characterized by relatively high storm surge frequencies, particularly with regard to the strong and moderate events, with frequencies of 0.4 and $3.3\,\mathrm{yr}^{-1}$, respectively (Fig. ~~3a~~4a and b). These values are approximately double the ~~secular means~~ long-term averages but consistent with the highest decadal frequencies computed from the ~~20th~~ 19th–20th century observations, which peak at $0.4\,\mathrm{yr}^{-1}$ in 1873–1882 and $0.3\,\mathrm{yr}^{-1}$ in 1896–1905, for strong events, and at $2.8\,\mathrm{yr}^{-1}$ in 1898–1907, for moderate events. The 1751–1769 frequency of weak events is $8.1\,\mathrm{yr}^{-1}$, i.e. 50 % higher than the long-term mean and higher than any 19th-20th century decadal mean, whose maximum is $6.4\,\mathrm{yr}^{-1}$ in 1958–1967 (Fig. ~~3c~~4c). In 1782–

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1792 the frequencies of strong, moderate and weak events are 0.3, 2.1 and 4.9 yr^{-1}, that is quite lower than in 1751–1769 and more similar to the modern values (Fig. ~~3a–c~~4a–c). The uncertainty bars associated to the 18th century data represent frequency ranges under the hypothesis that individual 18th century measurements are affected by a ~~3~~3-cm uncertainty (see Sect. 3). The annual number of events dealt with is small, nevertheless, it is interesting to notice that the number of storm surges is larger in certain years in the 18th century than in any year from 1872 onwards; in particular, strong events occur twice a year in 1756 and 1783 and never more than once a year from 1872 onwards (Fig. ~~3a~~4a) and the maximum annual number of moderate events since 1872 is 4, while 5 events are observed in 1754 and 6 in 1755 and 1756 (Fig. ~~3b~~4b); the maximum number of weak events is 11 in 1766, compared to 10 in 1911, 1960 and 1983 (Fig. ~~3c~~4c).

As a result, the meteorological conditions favourable to strong storm surges appear to be more frequent in the second half of the 18th century than in the late 19th and 20th centuries. This is consistent with Camuffo and Sturaro (2004), who, based on documentary data (Enzi and Camuffo, 1995), find that the second half of the 18th century is a period of relatively high frequency of flooding surges. The comparison should be taken cautiously because the sea level data used in the present work cover just 18 years in that period.

Note that if the sea level time series are filtered removing the fluctuations of periods longer than three months instead of six, the daily anomalies are generally smaller, in absolute value, nevertheless, the relative frequencies above the highest 5, 1 and 0.1 % thresholds do not differ significantly from those displayed in Fig. ~~3.~~4.

A cross-check is possible between the maximum daily sea levels reported by Temanza and Vianelli and the storm surge events listed in Enzi and Camuffo (1995) (Fig. ~~4~~5). They report only one, uncertain, event in the 1751–1769 period, namely on 14 January 1755 (Fig. ~~4a~~5a, circle). From Temanza's observations this event does not seem remarkable and several tens of events appear to be more severe. By contrast, the Temanza manuscript reports a flood at Venice on 13 October 1756, when sea level attains 75 cm above the CM, i.e. 100 cm above MSL (Fig. ~~4b~~5b, square); although it represents the eighth highest recorded event in the Venice time series, it is not listed in Enzi and Camuffo (1995). In the

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1782–1792 period Enzi and Camuffo (1995) list many more events: all the storm surges documented by direct witnesses correspond to sea level maxima at least 80 cm higher than the MSL (Fig. ~~4c~~5c and d, triangles), while uncertain events range from 20 to 120 cm above the MSL (Fig. ~~4c~~5c and d, circles). In December 1785–January 1786 multiple events are observed (see the box in Fig. ~~4c~~5c) while Enzi and Camuffo (1995) report a generic description of only one event in December 1785. A few strong events do not appear in Enzi and Camuffo (1995). A perfect correspondence between Enzi and Camuffo (1995) and the 18th century observations cannot be expected~~, however, the chronicles seems~~. However, the chronicles seem to report comparatively fewer events in 1751–1769 than in 1782–1792.

In the composite 1751–2004 time series the five highest daily sea level anomalies are observed on 4 November 1966 (101 cm), 30 November 1900 (84 cm), 25 February 1879 (78 cm), 24 December 1792 (77 cm), and 12 March 1783 (71 cm). The different data reliability does not allow to consider old and modern data strictly ~~homogeneous~~homogeneously, therefore the results must be taken cautiously~~, however,~~. However, even allowing for the uncertainties ~~on~~in the 18th century daily anomalies, the 4 November 1966 event represents a really outstanding event for centuries.

4.2 Monthly means and trends

Venice and Chioggia monthly MSLs are computed from the daily means corrected with the daily biases estimated as explained in Sect. 3. Following the criterion adopted by the PSMSL (2003), at least 15 days are required to compute a monthly mean. Figure ~~5~~6 shows the data availability on a monthly basis, represented by the percentage of days with observations. Venice monthly means can be obtained for January 1751–July 1756, October 1756–May 1757, January–March 1765, June 1765–June 1766, and January–December 1769; for Chioggia they can be computed for January 1782–November 1787, February 1788–January 1790, June 1790–June 1792, and September–December 1792. The time series of MSL, having applied the daily corrections discussed in Sect. 3.1, are displayed in Fig. ~~6~~7; the MSL errors (not shown) are approximately 0.5 cm at Venice and about 0.3 cm at Chioggia, obtained by combining the bias error and a 3 cm error on each measurement (see

Sect. 3). The 1751–1769 MSL at Venice is -25 cm, and the 1782–1792 MSL at Chioggia is 126 cm; these values represent the sea level averages relative to the CM at Venice and the sea floor at Chioggia. The time series are too short to obtain robust linear trend estimates. In particular, the Venice time series (Fig. 6a7a) spans 18 years, but it only includes a continuous 6.5year -year period (January 1751–May 1757) and two shorter periods separated by large gaps. Therefore, the physical significance of the estimated trend, namely (-0.24 ± 0.17) cm yr^{-1}, is questionable. The linear trend estimated from Chioggia data is (1.12 ± 0.26) cm yr^{-1}, that is much larger than the secular trend of (0.24 ± 0.01) cm yr^{-1} at Venice PS (Tsimplis, 2012), but consistent with recent decadal trends estimated from Chioggia Vigo data, namely (1.06 ± 0.23) cm yr^{-1} in 1989–2000 and (0.74 ± 0.20) cm yr^{-1} in 2001–2012.

Unfortunately, the 1779–1784 Chioggia time series of 5day 5-day Mean High Waters contains two (sometimes three) values per month, which is not enough to obtain reliable monthly means, nevertheless, . Nevertheless, they show good consistency with the more reliable 1782–1792 time series (Fig. 6b7b). The low sea level in February 1779 may be partly due to data scarcity, however, . However, that winter was characterized by persistent conditions of anomalously high atmospheric pressure with a February mean of 1031 hPa in Padua (Camuffo et al., 2002).

5 Conclusions

Thanks to multidisciplinary scientists, sea level observations are available for the Venice Lagoon during part of the second half of the 18th century. They are certainly of lower quality than modern data and, moreover, little is known about vertical reference levels, nevertheless the time series appear to be acceptable for an analysis. Clearly, the results should be interpreted with some tolerance.

Venice (1751–1769) and Chioggia (1782–1792) observations allow to obtain (gappy) time series of daily sea level means as well as of monthly means. It is possible to build a composite time series of daily sea level anomalies relative to the MSL by merging the 18th

century data and the observations made at Venice Punta della Salute since 1872, shortly after a regular tide gauge monitoring was started. Unfortunately, the absence of reliable information on vertical references prevents the construction of a unique homogeneous time series of relative sea level from 1751 to the present, and the short 18th century time series does not allow to estimate robust linear trends.

The composite time series allows to study the occurrence of storm surges and compare their frequencies in the second half of the 18th century and in the late 19th and 20th centuries. Storm surges appear to occur more often in the 1751–1769 period, while in the 1782–1792 period the frequencies of moderate and strong events are similar to those found in the late 19th century. Considering individual storm surges, the 4 November 1966 event appears to be the most severe one, not only since 1872, but also in comparison with any event in the 18th century time series.

Further data archaeology work is required to possibly recover missing information on vertical references as well as other sea level data, particularly to fill the gap between the 18th century data and the modern observations.

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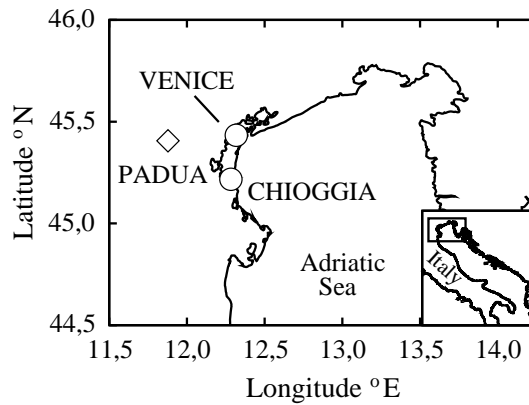
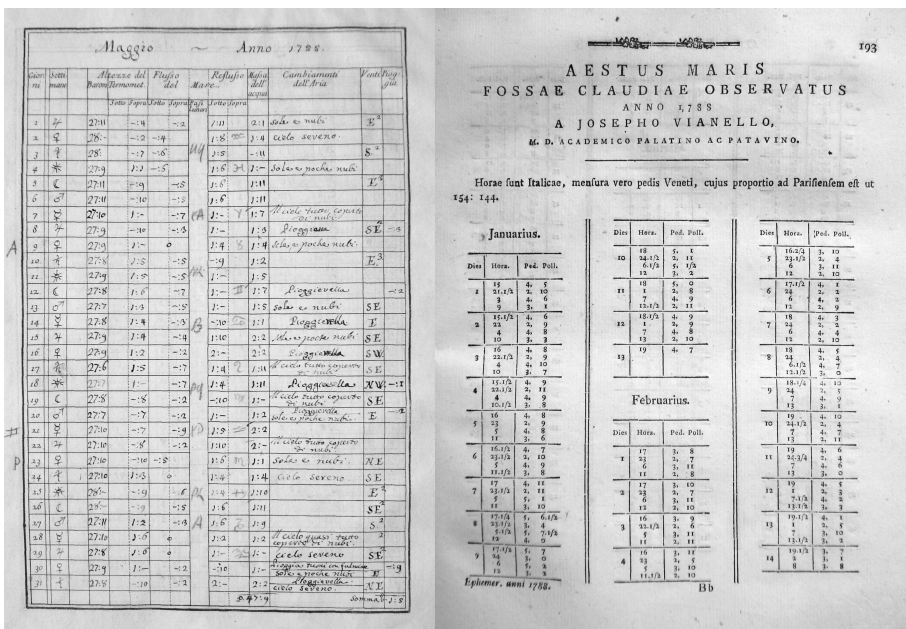**Figure 1.** Map of the northern Adriatic region.

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Figure 2. Temanza's manuscript for May 1755 (left; courtesy of the Historical Archive of INAF Astronomical Observatory, Padua). Chioggia data for January and February 1788 from (Vianelli, 1790) (right).
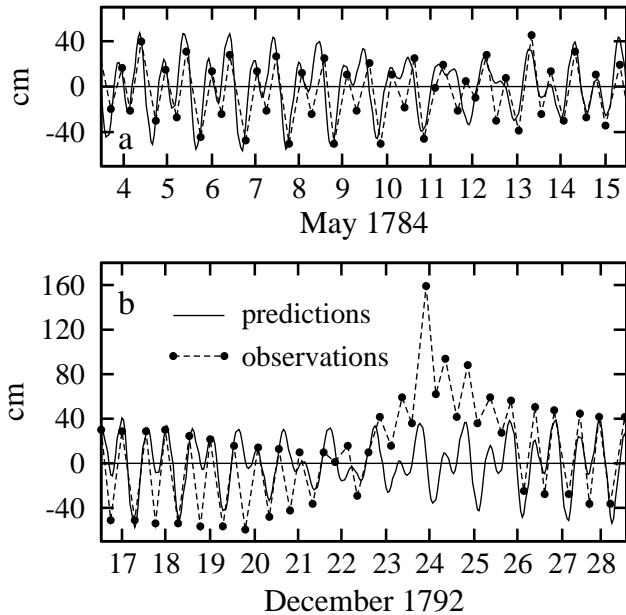
Figure 3. Comparison of observed data and tidal predictions at Chioggia from 4 to 15 May 1784 **(a)** and from 17 to 28 December 1792 **(b)**. Ticks on the horizontal axes correspond to noon.
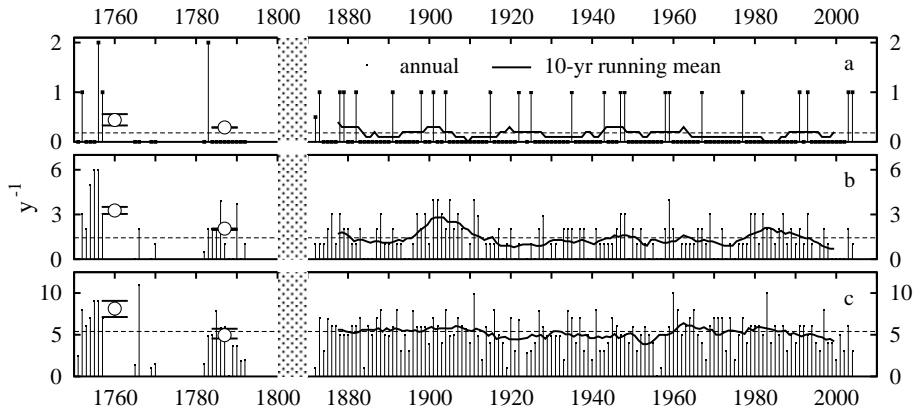
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Figure 4. Frequencies of daily sea level anomalies above 55 cm **(a)**, 37 cm **(b)** and 25 cm **(c)**, corresponding to the highest 0.1, 1 and 5 % of daily anomalies in 1872–2004, respectively. Annual values are represented by vertical bars, pseudo-decadal means by white circles and 10year 10-year running means by solid lines. Dotted horizontal lines represent the 1872–2004 means. The horizontal axis is interrupted for display purposes.
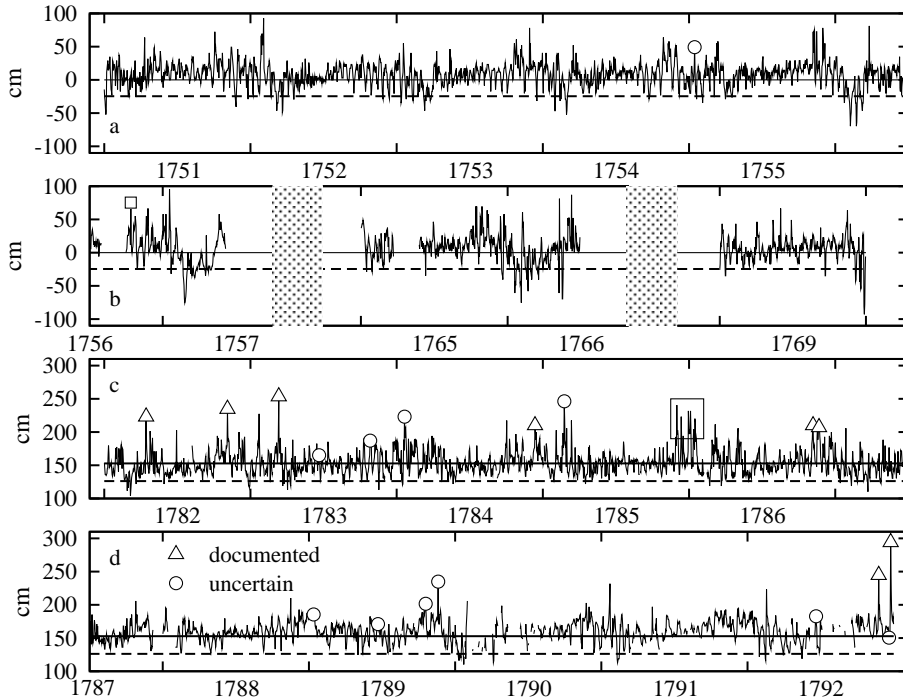
Figure 5. Daily sea level maxima for Venice **(a, b)** and Chioggia **(c, d)** in the original height scales converted to centimetres. Symbols indicate storm surge events quoted in Enzi and Camuffo (1995). The square in **(b)** indicates an event reported by Temanza (1751–1769) but not by Enzi and Camuffo (1995). The solid horizontal lines represent the CM at Venice **(a, b)** and the Mean High Water, as a proxy to the CM, at Chioggia **(c, d)**. The dotted horizontal lines represent MSLs. The horizontal axis in **(b)** is interrupted for display purposes. See also text for more details.
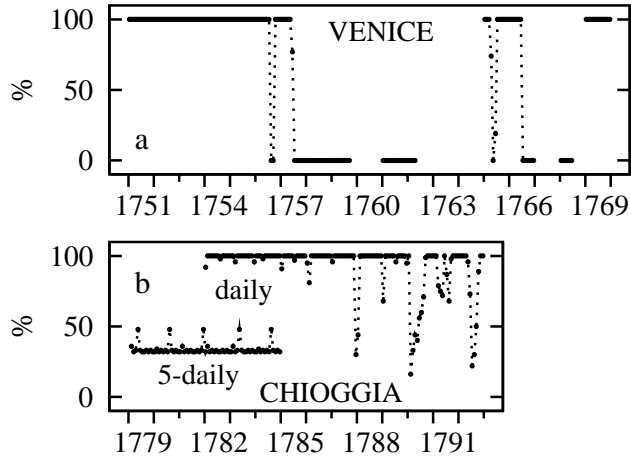
Figure 6. Monthly data availability at Venice **(a)** and Chioggia **(b)** as the percentage of days with data relative to the total. The absence of dots indicates that the ~~lack of~~ data ~~sources~~source is missing.
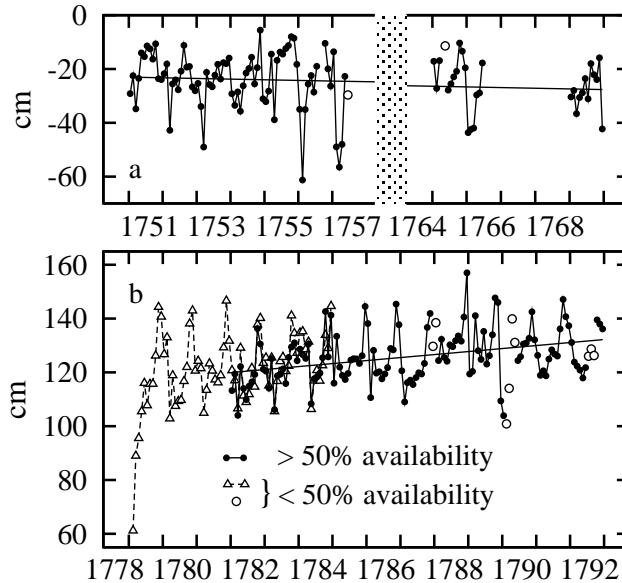
Figure 7. Corrected monthly means for Venice **(a)** and Chioggia **(b)**. Straight lines represent linear fits. The horizontal axis in **(a)** is interrupted for display purposes.